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# Photometry – The CIE V(λ) Function and What Can be Learned from Photometry

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The $V(\lambda)$ function, used in photometry, is an average action spectrum for the visual response of the human eye, and the matching of the spectral responsivity of photometers to $V(\lambda)$ is the most important criterion of photometers. Techniques have been developed to characterize photometers for spectral mismatch to the $V(\lambda)$ function and to correct for the mismatch errors as recommended in CIE Publication 69. These measurement techniques can be applied to broad-band UV radiometers and biological action spectra. As an example, two commercial UV radiometers have been analyzed for spectral mismatch errors using the spectral data of the Erythema function (McKinlay and Diffey – CIE 1987) and the UV hazard function (ANSI RP27.1) for measurement of solar spectrum and an FEL halogen lamp. The results of the analysis show dramatic variations of measured values. Suggestions are made on the calibration of such UV radiometers to improve the accuracy of measurements for these UV action spectra.

## Introduction

Measurements of UV radiation for various hazard effects can be performed by spectroradiometry or broad-band measurements. Broad-band measurements can be accomplished with simpler instrumentation and is more convenient than spectroradiometry. However, with broad-band radiometers, errors due to the mismatch of their spectral responsivity to the action spectrum is inevitable. This has also been the case with photometry that has 75 years history. The $V(\lambda)$ function, the spectral luminous efficiency function of a photopic vision, is an average action spectrum for the visual response of the human eye. The matching of the spectral response of photometers to $V(\lambda)$ was poor in the early days, and it is still the most important criterion of photometers. Techniques have been developed to characterize photometers for spectral mismatch to the $V(\lambda)$ function (term, $f_1'$), infrared leakage, deviation from the cosine response, etc. and to correct the errors due to these effects [1]. These measurement techniques for photometers can be applied to broad-band UV radiometers.

In this paper, the methods for evaluation and correction for spectral mismatch errors in photometry are first described. Then, as an application of such methods to broadband UV measurements, two commercial UV radiometers designed for measurement of the erythema effect have been analyzed for $f_1'$ and the spectral mismatch errors for the Erythema function (McKinlay and Diffey – CIE 1987 [2]) and the UV hazard function (ANSI RP27.1 [3]) in the measurement of the solar spectrum and an FEL halogen lamp standard. Based on the results, suggestions are made on the calibration of such UV radiometers to improve the accuracy of measurements of the quantities based on these UV action spectra.

## 2. Spectral mismatch correction

A photometric quantity, such as luminous intensity or illuminance, represents the visual response to the human eye, and is defined by,

$$X_{\mathrm{v}} = K_{\mathrm{m}} \int_{\lambda} S_{\mathrm{e}}(\lambda) V(\lambda) \mathrm{d}\lambda \ , \tag{1}$$

where $S_{\mathrm{e}}(\lambda)$ is the spectral concentration of radiation and $K_{\mathrm{m}}$ is the maximum spectral luminous efficacy (683 lm/W) [4]. Thus, in order to measure a photometric quantity, a photometer must have a relative spectral responsivity matched to $V(\lambda)$. However, no photometer can be perfectly matched to this function, and an error occurs when a photometer measures a light source having a spectral power distribution different from the calibration source (the source against which the photometer is calibrated). Fig. 1 is an example of a photometer with a significant mismatch to $V(\lambda)$. If the photometer is calibrated against CIE Illuminant A (2856 K Planckian radiation), the photometer measures much lower values in the blue region and higher values in the red region. For example, if the photometer measures a day light fluorescent lamp, a red LED, and blue CRT phosphor, as also shown in Fig.1, the errors for measurement of these light sources are +6 %, +27 %, and -41 %, respectively. However, these errors can be corrected by the calculations as described below.

If the photometer's relative spectral responsivity and the spectral distributions of the test source and standard source are known, the spectral mismatch error can be corrected by the spectral mismatch correction factor $F$ as given by

$$F(S_{\mathrm{t}}, S_{\mathrm{s}}) = \frac{\int_{\lambda} S_{\mathrm{t}}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda \ \int_{\lambda} S_{\mathrm{s}}(\lambda)\, s_{\mathrm{rel}}(\lambda) \mathrm{d}\lambda}{\int_{\lambda} S_{\mathrm{t}}(\lambda)\, s_{\mathrm{rel}}(\lambda) \mathrm{d}\lambda \ \int_{\lambda} S_{\mathrm{s}}(\lambda)\, V(\lambda)\, \mathrm{d}\lambda} \ , \tag{2}$$

where $S_{\mathrm{t}}(\lambda)$ is the spectral power distribution of the test source, $S_{\mathrm{s}}(\lambda)$ is the spectral power distribution of the standard source, $s_{\mathrm{rel}}(\lambda)$ is the relative spectral responsivity of the photometer, and $V(\lambda)$ is the spectral luminous efficiency function. The photometer signal is multiplied by this factor to obtain a corrected result.

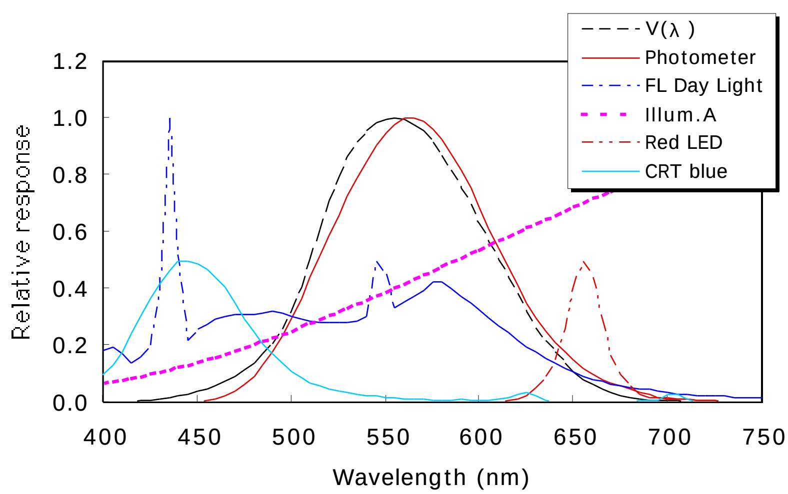


Figure 1. Spectral mismatch of a photometer measuring various light sources

From the spectral mismatch correction factor $F(S_{\mathrm{t}}, S_{\mathrm{s}})$, the relative error $\varepsilon$ of measurement due to the spectral mismatch (as discussed above for measurement of a fluorescent lamp, a red LED, and a blue CRT phosphor) is given by

$$\varepsilon = \frac{1}{F(S_t, S_s)} - 1 \; . \tag{3}$$

By applying the correction factor $F(S_t,S_s)$ to the measured results, the spectral mismatch errors will be theoretically eliminated.

## 3. Evaluation of the spectral mismatch of a photometer

The degree of mismatch of the relative spectral responsivity to the $V(\lambda)$ function is evaluated by using a term $f_1'$ as recommended in reference [1]. $f_1'$ is an evaluation index used to rate the quality of photometers in terms of spectral mismatch, and cannot be used for correction purposes. $f_1'$ is calculated from the relative spectral responsivity of the photometer according to the equation

$$f_1' = \frac{\int_\lambda \left| s^*_{\mathrm{rel}}(\lambda) - V(\lambda) \right| \mathrm{d}\lambda}{\int_\lambda V(\lambda)\mathrm{d}\lambda} , \tag{4}$$

where $s^*_{\mathrm{rel}}(\lambda)$ is a normalized relative spectral responsivity of the photometer, as given by

$$s^*_{\mathrm{rel}}(\lambda) = \frac{\int_\lambda S_A(\lambda)\, V(\lambda)\mathrm{d}\lambda}{\int_\lambda S_A(\lambda)\, s_{\mathrm{rel}}(\lambda)\mathrm{d}\lambda}\; s_{\mathrm{rel}}(\lambda) , \tag{5}$$

and $S_A(\lambda)$ is the spectral distribution data for CIE Illuminant A (the recommended calibration source for photometry). This calculation is illustrated in Fig. 2. In eq. (5), $s^*_{\mathrm{rel}}(\lambda)$ is normalized in such a way that the total area of the function weighted by $S_A(\lambda)$ is equal to the total area of $V(\lambda)$ weighted by $S_A(\lambda)$. The differences between $s^*_{\mathrm{rel}}(\lambda)$ and $V(\lambda)$, shown as shaded areas in Fig. 2, are the errors of the photometer for monochromatic radiation of wavelength $\lambda$, when the photometer is calibrated against the CIE Illuminant A. The $f_1'$ value of the photometer in this figure is 11.9 %.

The spectral match of a photometer or an illuminance meter is generally considered as high quality for $f_1' < 3$ %, medium quality for 3 % < $f_1'$ <8 %, and poor quality for $f_1'$ > 8 % [5]. Some recent commercial photometers achieve $f_1'$ values of less than 2 %. The errors of photometers for various discharge lamps regarded as "white light" sources tend to be within the $f_1'$ value of the photometer. However, the errors for colored light sources such as traffic signals, CRT displays, LEDs, etc.,

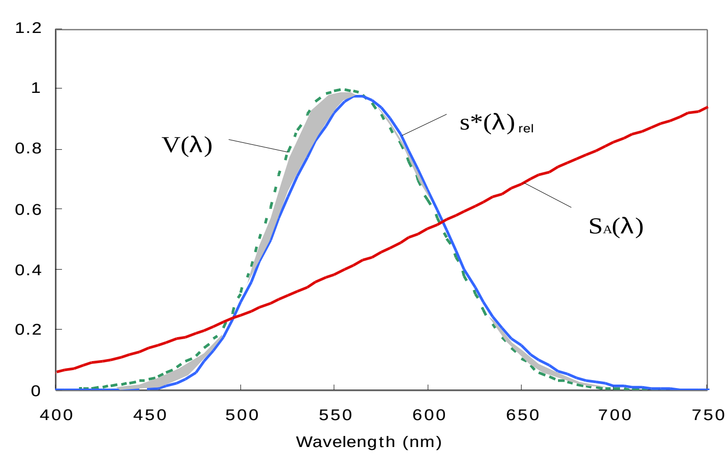


Figure 2. Calculation of CIE $f_1$'

can be much larger than the $f_1'$ value.

This analysis of $f_1'$ assumes that the photometer is calibrated against CIE Illuminant A. If a photometer is calibrated against other sources, $S_A(\lambda)$ can be replaced by the spectral distribution of the calibration source to be used.

The characterization of photometers for quantities other than spectral mismatch, such as for infrared leakage of response, cosine response, linearity, etc. as described in reference [1], can also be applied to UV radiometers.

## 4. Application to UV radiometers

The spectral mismatch correction technique in photometry can be applied to UV broadband measurements where the $V(\lambda)$ function is replaced by a particular UV action spectrum. Two commercial UV radiometers, designed for measurement of UV radiation hazards, are analyzed for errors in the measurement for the McKinlay/Diffey CIE 1987 Erythema function [2]. Additionally, the UV radiometers have been analyzed for the UV hazard function $S(\lambda)$ in ANSI/IESNA RP27.1 [3] as they might also be used for measurement in this function.

The relative spectral responsivity of the two UV radiometers together with CIE Erythema function are shown in Fig. 3. It is assumed that the radiometers are calibrated against an FEL lamp at 3100 K (a typical type of lamp used as a spectral irradiance standard) and used to measure the solar spectrum. In this case, $V(\lambda)$ in eqs. (2-5) is replaced by the Erythema function, $S_s(\lambda)$ in eq. (2) and $S_A(\lambda)$ in eq. (5) are the FEL lamp spectrum, and $S_t(\lambda)$ in eq. (2) is the solar spectrum. The spectral mismatch correction factors ($F$ as given by eq. (2)) were calculated to be 0.48 for radiometer 1 and 0.19 for radiometer 2. The errors of radiometers 1 and 2 ($\varepsilon$ as given by eq. (3)) are 107 % and 414 %, respectively. The $f_1'$ values (given by eqs. (4) and (5)) of the two radiometers for the Erythema function are 38 % and 76 %, respectively.

The same analyses have been made for the case that these two UV radiometers were used to measure weighted irradiance for ANSI/ IESNA RP27.1 $S(\lambda)$ function as shown in Fig. 4. In

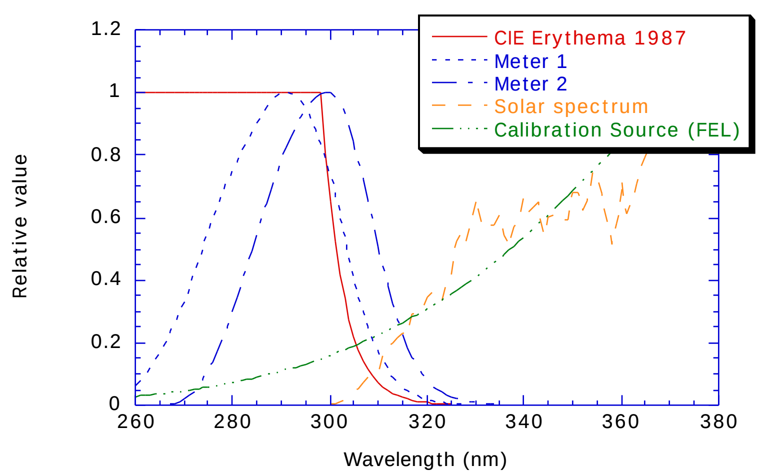


Figure 3. Spectral responsivities of two UV radiometers plotted with CIE Erythema 1987 function and spectral power distribution of an FEL lamp and the Solar spectrum.

this case, $V(\lambda)$ in eqs. (2-5) is replaced by the RP27.1 $S(\lambda)$ function. The spectral mismatch errors ($\varepsilon$ ) of the two UV radiometers would be 470 % and 1420 % (one order of magnitude higher), respectively. The $f_1'$ values of the two radiometers for the RP27.1 $S(\lambda)$ function would be 58 % and 89 %, respectively.

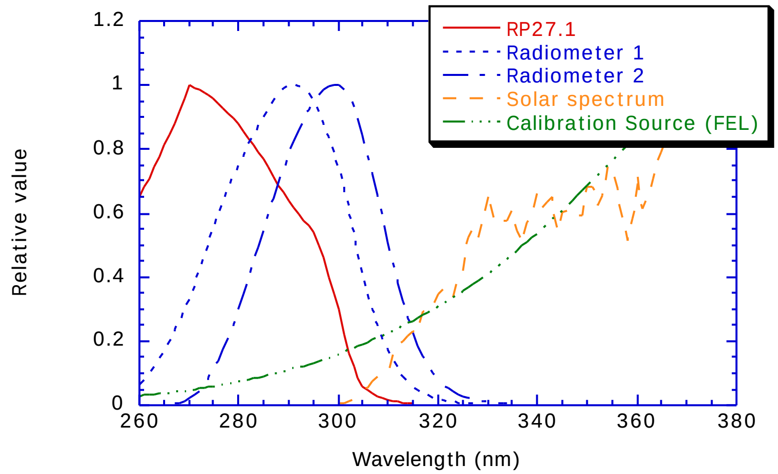


Figure 4. Spectral responsivities of two UV radiometers plotted with ANSI/IESNA 27.1 $S(\lambda)$ and spectral power distributions of an FEL lamp and the Solar spectrum.

These results indicate that, with the two UV radiometers analyzed, the solar spectrum in CIE Erythema function or in RP27.1 $S(\lambda)$ cannot be measured with an acceptable accuracy (expanded uncertainties of 5 % to 10 % with $k$=2 are desired) if these UV radiometers are calibrated against an FEL lamp. However, these errors will be theoretically zero if the spectral mismatch correction factor is applied to the measurement result. The correction factors vary significantly depending on which action spectrum is used, what light source is measured, and what light source is used as the calibration source.

## 5. Calibration methods for UV radiometers

When UV radiometers with a current level of spectral mismatch are to be used, the UV radiometers should have different calibration factors for different types of sources in order to keep the measurement accuracy within an acceptable level. The type of the particular light source(s) for which a UV radiometer is calibrated against should be clearly specified. UV radiometers can be accurately calibrated using the following methods. Two cases are assumed depending on the availability of the relative spectral responsivity data for the UV radiometer.

**Case 1)** The relative spectral responsivity of the radiometer is known.

(1) Calibrate the radiometer with any available standard sources (FEL lamp, deuterium lamp, etc.).
(2) Calculate the spectral mismatch correction factor $F$ for the particular source to be measured.

**Case 2)** The relative spectral responsivity of the radiometer is unknown.

(1) Prepare an actual UV source to be measured by the test UV radiometer.
(2) Measure the UV source at a certain distance from the UV source with a spectroradiometer or a reference UV radiometer (corrected by the spectral mismatch correction factor for this UV source), and determine the weighted irradiance based on a specific action spectrum.

(3) Calibrate the test UV radiometer under irradiation by the UV source at the calibrated point.

## 6. Conclusion

The methods for evaluation and correction for spectral mismatch errors in photometry can be applied to broadband UV measurements for a specific action spectrum. Two actual UV radiometers were analyzed for $f_1'$ and for the spectral mismatch errors for the CIE 1987 Erythema function and the UV hazard function (ANSI/IESNA RP27.1). The spectral mismatch errors for these UV radiometers were found to be unacceptably large if these radiometers were calibrated against an FEL lamp and measured the solar spectrum, for example.

Such spectral mismatch errors can be eliminated by applying the spectral mismatch correction factors as used in photometry. Two methods for accurately calibrating UV radiometers are suggested; one method based on the spectral mismatch correction using the relative spectral responsivity of the radiometer, and another method utilizing an actual UV source as a calibration source that is the same type as the UV source to be measured. If more than two types of sources are to be measured, calibration factors for each type of source is to be obtained and selected according to which light source is to be measured.

The spectral match of UV radiometers with an action spectrum function can be evaluated by $f_1'$. The spectral responsivity of UV radiometers should be improved so that the $f_1'$ value is reduced. The goal in the near future would be $f_1'$ values of less than 10 %.

Other characteristics of UV radiometers, such as leaked sensitivity outside the UV region, angular response (deviation from the cosine response), and linearity of response can also be evaluated by applying the practice used in photometry [1].

## References


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